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ORIGINAL ARTICLE

The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India

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Abstract Alien invasive species cause significant impacts on ecosystems and economies, but the impacts on human well-being and livelihoods are less well known. Negative impacts can be particularly severe when caused by floating aquatic plants, which can reduce access to freshwater for extraction and navigation, reduce the harvest of fish and other resources, and change water cycling and chemistry. This paper reviews and discusses some of these impacts globally and then concentrates on the case study of Wular Lake, India. Wular is the largest freshwater lake in Jammu and Kashmir state and is highly important for local livelihoods through the provision of a range of services, including fish and edible aquatic plants, and water to local communities. The supply of these services has decreased due to a long history of environmental degradation, and recent invasions by the floating plants *Azolla cristata* and *Alternanthera philoxerodies* (alligator weed) have further impacted human well-being. Here, we review the published literature about these invasions, present information from interviews with locals living near Wular Lake, and review the global literature about invasive floating plant species to assess the present and predict the future impacts of these species. We find that the implications of these invasions for livelihoods reliant on lake resources and services provide good justification for management efforts. We discuss some options and challenges to such a management program.

Keywords Alligator weed · *Alternanthera philoxeroides* · *Azolla cristata* · Biological invasions · Ecosystem services · Kashmir · Livelihoods, poverty

Introduction

Non-native (alien) invasive species are well recognized as having large impacts on ecosystems across the globe (Pejchar and Mooney 2009; Le Maitre et al. 2011; Shackleton et al. 2014). The ecological and financial impacts of invasive species have been relatively well studied, but the consequences of these species for human livelihoods and well-being have received much less attention (but see Perrings 2007; Shackleton et al. 2007, 2015; Nuñez and Pauchard 2010; Kull et al. 2011). Despite this, there is good reason to believe that such impacts may be large because invasive species can reduce the supply of ecosystem services which are important for humans (Pejchar and Mooney 2009; Aloo et al. 2013; van Wilgen and Richardson 2014). This loss of ecosystem services is likely to cause the most severe impacts to human well-being in cases where local economic systems are closely tied to the harvest of biological resources, and/or where subsistence agriculture is practiced. Such economic systems are most common in poorer countries and rural

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areas where human populations are often highly vulnerable to environmental changes (Perrings 2007).

Shackleton et al. (2007) developed a framework for how invasive species can impact upon rural livelihoods. They argue that the outcomes from an invasion depend on factors including the rate of spread and density of the invasive species, the extent to which it is incorporated as a beneficial element into local economies (e.g., as food or firewood), and the vulnerability of local communities. This model recognizes that in some cases invasive species can be incorporated into local livelihoods and may cause net benefits (Shackleton et al. 2007). The vulnerability of a community is the extent to which environmental changes, such as those caused by invasive species, can affect livelihoods. Communities with high vulnerability are characterized by a lack of household savings, reliance upon subsistence agriculture, and reliance upon one or a few products extracted from the environment. Such communities are likely to have little resilience if an invasive species alters the flow of important ecosystem services. Within this framework, Shackleton et al. (2007) identified that the invasions that cause the greatest decline in human welfare are those that provide little or no benefit to locals, are caused by species that are strongly competitive and that greatly alter local ecosystems, and that occur in regions where human communities are highly vulnerable.

There are few well-developed case studies of consequences from invasive species for human well-being (Shackleton et al. 2007, 2014), but those that have been conducted on floating aquatic plants indicate that these species can have large impacts on human communities (see Table 1). This result is not surprising given the importance of wetlands to human livelihoods, and given the extent to which invasive species can affect the provisioning of wetland ecosystem services (Kumar et al. 2011). These impacts can result from changes to food webs that occur as floating plants overgrow a waterbody and shade out other aquatic plants (Villamagna and Murphy 2010), loss of fisheries, reduced water availability (Boyd 1987; Aloo et al. 2013), changes in water chemistry (Aloo et al. 2013), and increased human disease prevalence from creation of breeding habitat for vectors such as mosquitoes (Kasulo 2000) (Table 1). Within the framework of Shackleton et al. (2007), such impacts present the worst invasion scenarios for livelihoods when they occur in regions with vulnerable human communities. Invasive aquatic plants also usually offer little to no beneficial resources to local households.

An example of the impacts from invasive floating plants is the arrival and spread of giant salvinia (*Salvinia molesta*) in the Sepik River of Papua New Guinea. After establishment in the 1970s, this species grew into thick mats covering much of the river and connected lagoons. The river serves as the main mode of transport for local villages, and the invasive species made it impossible for residents to access schools, markets, and medical facilities (Table 1). Additionally, the river provides a main source of protein (fisheries) and carbohydrate (sago palm), and access to these subsistence and commercial resources became limited (Thomas and Room 1986). There are reports of malnutrition and starvation as a result, and several villages had to be evacuated before the invasion was brought under control by an internationally funded biological control program (Thomas and Room 1986).

The impacts of invasive species are often associated with other changes to ecosystems (MacDougall and Turkington 2005). In freshwater systems, for example, growth, spread, and impacts of invasive species are often enhanced by other drivers such as increased nutrient levels, altered flow regimes, and the loss of top predators due to overharvesting (Gherardi 2007). This can make it difficult to determine the exact impacts of an invader and the potential benefits that would accrue from its removal. Despite this, in many cases invasive species are clearly primary drivers of ecosystem change, and their removal would be expected to lead to improvements. Africa's Lake Victoria, for example, has been impacted by a range of environmental changes that enhanced its suitability for the establishment and spread of the floating plant water hyacinth (*Eichhornia crassipes*). This species invaded during the 1980s and directly and indirectly threatened approximately 30 million people through the loss of fisheries, open water for transport, and electricity production, along with reduced flows of other ecosystem services (Aloo et al. 2013). While this invasion was partly the result of previous alterations to the lake, large benefits have been realized from the control of water hyacinth through the introduction of biocontrol agents (Wilson et al. 2007; Aloo et al. 2013). These benefits to the environment and human well-being have been achieved without full restoration of the lake.

This paper describes the recent invasion of Wular Lake in the Indian state of Jammu and Kashmir (Fig. 1) by the floating plant species *Azolla cristata* and *Alternanthera philoxeroides* (alligator weed). We review the current state of Wular Lake, how it has changed over recent decades, and the reliance of local communities upon ecosystem services provided by the lake. Despite an extensive history of environmental change in Wular Lake, many of the long-term environmental problems could be managed at reasonable costs to maintain ecosystem service delivery (Wetlands International 2007). The recent invasions, however, threaten the potential for restoration and raise the possibility of irreversible losses of ecosystem services and declines in human well-being.

The invasions dealt with here occurred recently, and their impacts are still being realized. Wular Lake has not been well studied, and because few data have been regularly collected to quantify the ecosystem services extracted from it, we present three different lines of evidence for the type and level of impacts from the new invaders. First, we use the scientific research that has so far been conducted on Wular Lake to

Table 1 A subset of ecological components, ecological processes, and ecosystem services (sensu Ramsar (2008)) provided by large lakes and rivers, the ways that these services are affected by invasive floating aquatic plants, and the negative effects on human well-being

Ecosystem factor	Mechanisms of impact from invasion by floating plants	Consequences for human well-being/livelihoods	Citations
Ecological components affected			
*Habitat types	- Dense surface mats are a new (or expanded) type of habitat that reduces open water and restricts boat transport	- Decreased mobility, leading to loss of access to schools, medical facilities, markets, etc., ultimately leading to loss of trade and incomes - *Access to waterbodies for fishing and plant harvesting becomes limited	Thomas and Room 1986; Boyd 1987; Howard and Harley 1998; Aloo et al. 2013; this study
*Water regime	- Dense mats increase evapotranspiration and sedimentation, leading to reduced depth, surface area, and volume of waterbody - Dense mats can channelize and speed up water flow	- *Loss of water availability and opportunity for boat transport - Increased flood levels leading to loss of pasture and housing, erosion, and damage to infrastructure	Holm et al. 1969; Thomas and Room 1986; Boyd 1987; Howard and Harley 1998; Aloo et al. 2013; Strayer 2010; Langeland 1996; this study
Ecological processes affected			
*Notable species interactions, including grazing, predation, competition, diseases, and pathogens	- Floating aquatic plants provide habitat for nuisance animals and disease vectors (e.g., mosquitoes, snails)	- *Increased prevalence of nuisance animals and disease (e.g., malaria, bilharzia)	Esiwerth et al. 2000; Kasulo 2000; Twongo 1996; this study
Provisioning services affected			
*Food for humans (fisheries)	- Reduce oxygen penetration - Interfere with setting and retrieving fishing gear - Change species composition, with reductions in populations of desirable species and their food sources	- *Loss of food source and food security (with ensuing health impacts) - *Loss of income for households involved in commercial fishing - Increased cost of food for consumers	Villamagna and Murphy 2010; Coetzee et al. 2014; Brundu 2015; Holm et al. 1969; Thomas and Room 1986; Howard and Harley 1998; Aloo et al. 2013; this study
*Food for humans (aquatic plants)	- Outcompete desirable species	- *Loss of human food source (e.g., water chestnut) and food security (with ensuing health impacts) - *Loss of incomes for gatherers and growers - Increased cost of food for consumers	Thomas and Room 1986; this study
*Food for livestock	- Outcompete desirable species	- *Aquatic invasive reduces available fodder - *Loss of incomes for livestock holders	This study
*Drinking water for humans and/or livestock; water for irrigated agri-culture; water for industry	- Increased evapotranspiration - Block pipes and channels - Reduce water holding capacity by increasing sedimentation	- *Amount and timing of water provision is altered, leading to reduced availability for consumption by humans and livestock consumption, irrigation, and hydroelectricity production	Holm et al. 1969; Aloo et al. 2013; this study
Regulating services affected			
*Water purification/waste treatment or dilution	- Dense mats impede water flow - Dense mats reduce oxygen and light penetration, outcompeting underwater plants - Change water chemistry and quality through mechanisms such as eutrophication	- Water quality is reduced for consumption by humans and livestock - *Reduced productivity of fishes and aquatic plants for human harvest	Holm et al. 1969; Eiswerth et al. 2000; Villamanga and Murphy 2010; Brundu et al. 2012; Aloo et al. 2013; Brundu 2015
Cultural services affected			
*Cultural Heritage	- Invasive plants alter supply of essential ecosystem services, making traditional livelihoods untenable	- *Communities have to relocate and develop new livelihood strategies (cultures)	Thomas and Room 1986; this study
Recreational hunting and fishing; water sports	- Access to waterbodies and infrastructure (e.g., docks) is prevented by dense plant mats	- Loss of recreational value from boating, swimming, waterskiing, fishing, etc.	Langeland 1996; Brundu et al. 2013
Esthetic and "sense of place" values; Other recreation and tourism	- Dense mats decrease visual appeal of waterbodies and reduce populations of charismatic species (e.g., birds)	- Loss of esthetic values of waterbodies, reduced property prices, decreased tourism revenue	Holm et al. 1969; Charles and Dukes 2007; Eiswerth et al. 2000

A component/process/service (with asterisk) has been recorded as negatively impacted by the *A. cristata* and alligator weed invasions of Wular Lake. Note that this is not a full description of the benefits from large lakes and rivers, nor of the impacts of floating aquatic plants. Instead, it is the subset for which impacts arising from the invasions of *A. cristata* and alligator weed have already been recorded or suggested for Wular Lake

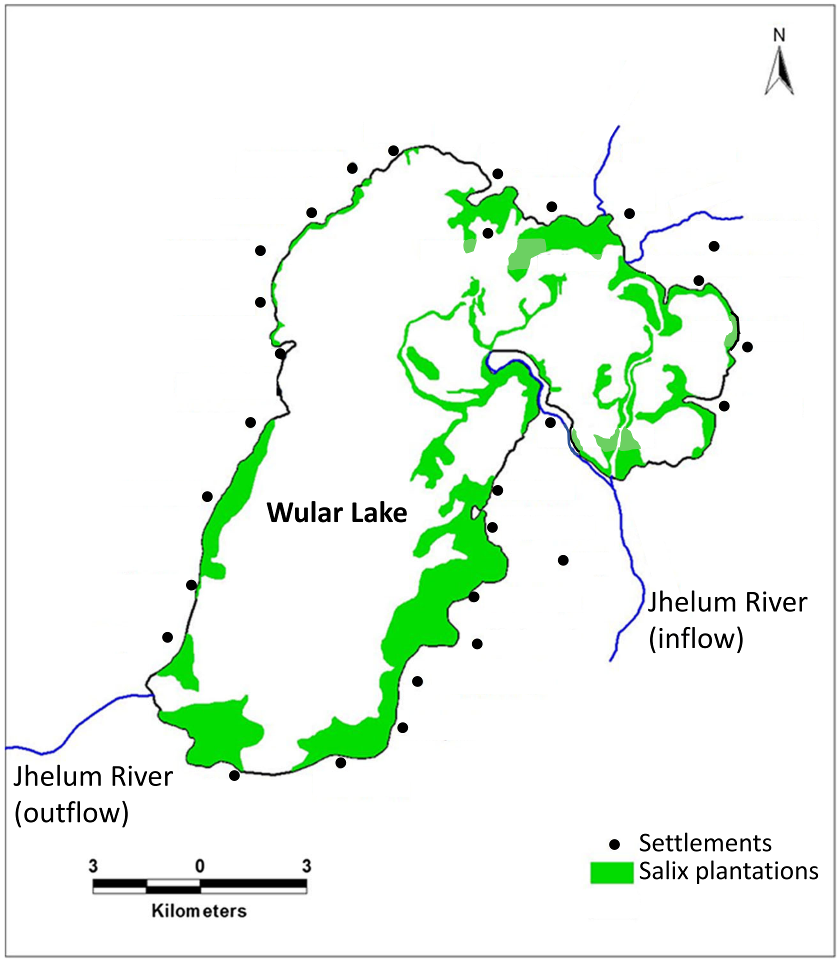

Fig. 1 Map of Wular Lake—located in Jammu and Kashmir state in northern India—showing human settlements and willow (*Salix* spp.) plantations along the shoreline of the Lake

describe the arrival, spread, and early impacts of alligator weed and *A. cristata*. Second, we supplement this evidence with the scientific literature from other social-ecological systems where the impacts of floating aquatic plants on human well-being have been studied. The collated results from these first two lines of evidence are presented in Table 1. As a third line of evidence, we present a range of quotes related to the invasive plants that we gathered during interviews of local community members during June 2014. This paper thus provides a survey of the impacts of invasive floating aquatic species on human well-being and identifies which of these impacts have already been recorded in Wular Lake. Given the rapid spread of alligator weed and *A. cristata* and the impacts that have already been recorded (see below), it is reasonable to expect that many of the impacts in Table 1 that have not yet been recorded in Wular Lake may be seen in the future, and that the impacts already recorded will intensify. Local communities already experience high poverty and vulnerability levels and have few options to substitute for lost ecosystem services.

The social-ecological system of Wular Lake

Wular Lake is the largest freshwater lake in India. It is located at 1580 m elevation in the Kashmir Valley and has a seasonal maximum surface area of 61.7 km^2 (Fig. 1; Bhat and Pandit 2014). The main inflow is the Jhelum River that in turn receives a consistent base flow of snow and glacial meltwater from the surrounding Himalayan and Pir Panjal mountain ranges (ISRO 2010). The Jhelum River then flows out through Kashmir and into Pakistan where it is a major tributary of the Indus River. Flow is highly seasonal and greatest during late spring and early summer as high rainfall combines with snowmelt.

Despite its large size, Wular Lake has a maximum depth of just 6 m and the seasonality of inflowing rivers creates large annual changes in the lake's depth and extent. Between September 2010 and August 2011, the depth at a point near the center of the lake ranged from 1.0 m in January to 5.5 m during May (Shah and Pandit 2012). The total surface area ranges from 12.2 to 61.7 km^2 as fringing wetlands are seasonally inundated and exposed (Bhat and Pandit 2014).

The Kashmir Valley has experienced rapid human population growth over recent decades, with much of this occurring in the catchment of Wular Lake. The two administrative districts that border the lake—Bandipora and Baramulla—grew in population by 4 and 3.5 times, respectively, between 1961 and 2011 (censusofindia.gov.in). These districts have high poverty rates; at the Jammu and Kashmir state poverty level of ~ US$10/month, 31.1 and 26.5% of their populations live below the poverty level, compared to a state average of 21.6% (DES 2014). Poverty levels in villages directly on the shores of Wular Lake are reported to be as high as 41–52% (Wetlands International 2007). Levels of education are also low, with 2011 literacy rates of 47% in Bandipora and 54% in Baramulla districts, far below those at the Jammu and Kashmir state (67%) or whole India levels (73%; censusofindia.gov.in).

The 31 villages, comprising almost 11,000 households, located on the shoreline (Fig. 1) of Wular Lake are highly dependent upon extraction of fish, aquatic plants, and water from the lake. The main aquatic plants harvested are water chestnut (*Trapa natans*) and Nelumbo (*Nelumbo nucifera*), both of which are collected for human food, and assorted wetland grasses (e.g., *Nymphoides peltata*, *Phragmites* sp.) for fodder (Wetlands International 2007). Aquatic fodder plants have higher nutrition than terrestrial grasses and increase livestock milk yields and therefore are very important for local communities (Shah et al. 2010). A variety of fishes are captured and either used for subsistence or sold in local markets. Water is extracted from Wular Lake for agricultural purposes (e.g., irrigation of rice paddies and orchards), and several towns extract water for municipal use. Wular Lake has become an important resource for the supply of fuelwood to local communities, and 34 km^2 of fringing wetlands have been planted with fast growing willow trees (*Salix* spp.) over the last century to support this (Fig. 1). These trees have raised soil levels and converted these wetlands to uplands (Wetlands International 2007).

Seasonal fluctuations in lake storage allow its volume to grow during high inflows and moderate the flow of water downstream, reducing flood size and providing a stable supply of water to support hydroelectric generation at three power plants on the River Jhelum. Because there are few other sources of electricity in the region, the amount of water stored in Wular Lake and the seasonality of outflow have a direct bearing on day-to-day electricity availability in Kashmir and other states in northern India (Wetlands International 2007).

The high productivity of the lake and its large size relative to other freshwater resources make Wular Lake an important habitat for wildlife, including many species of migratory waterbirds. Wular Lake was included in 1986 as a Wetland of National Importance under the Wetlands Program of the Indian Ministry of Environment and Forests. In 1990, it was designated as a Wetland of International Importance under the Ramsar Convention for its biodiversity and socio-economic values (Wetlands International 2007). Although the number of migrating birds that use the lake has decreased over recent decades, largely as a result of the lake itself shrinking (see below), it remains an important resource for dozens of migratory species, including several that are globally threatened (Rahmani 2012).

Environmental changes

Growing human populations have caused many land use changes across the Kashmir Valley. These include decreased forest area as trees are cut for fuel and to make way for agriculture and settlement, increased quarrying activity, and encroachment of willow plantations and agricultural fields into wetlands (Zaz and Romshoo 2012). A recent study classified 48.3% of the Kashmir Valley as having *high* or *very high* erosion risk (Zaz and Romshoo 2012). In the 2115-km^2 Pohru watershed adjacent to Wular Lake, the area of land classified as *dense forest* decreased from 26 to 16%, while the percentage of *built up* land more than doubled to 6.8%, between 1992 and 2001 (Zaz and Romshoo 2012). Over the same period, the area of *bare* land increased from 5.1 to 8.9%, and the areas of *agriculture* and *horticulture* increased from 12.3 to 15.8 and from 1.6 to 5.9%, respectively (Zaz and Romshoo 2012). Another recent study looked at changes in land cover within the 5-km zone surrounding the shores of Wular Lake between 1992 and 2008. The area classified as *forest* decreased from 93 to 32 km^2, the area of *built up* land increased from 7 to 52 km^2, and *marshy* wetland area decreased from 85 to 5 km^2 (Mushtaq and Pandey 2014).

These changes have caused the seasonal maximum size of Wular Lake to decline from an estimated 157.7 km^2 in 1911 to 86.7 km^2 in 2007 (Wetlands International 2007), with a more recent estimate of 61.7 km^2 (Bhat and Pandit 2014). We note here that there are divergent estimates of the size of Wular Lake, presumably resulting from its high seasonality and whether fringing wetlands are included. Despite these differences, there is agreement that the lake has shrunk in surface area by approximately half over the last century (Wetlands International 2007; Bhat and Pandit 2014). The strongest drivers of this decrease have been increases in inflowing sediment, expansion of willow plantations, and the construction of dykes to convert wetlands to agricultural land (Wetlands International 2007). Concurrent with this decline in lake and wetland area has been a large increase in nutrient levels, attributable to decreased filtering by wetlands and increased agricultural fertilizer use (Wetlands International 2007). For example, seasonal phosphorus concentrations in the lake increased from 0.0–103 μg/L in 1992 (Kundangar et al. 1992; Wetlands International 2007) to 102–297 μg/L between October 2010 and September 2011 (Shah and Pandit 2012). Nitrogen levels have also increased, and the lake is now classified as eutrophic (Wetlands International 2007).

The provisioning of many important ecosystem services has been reduced by the changes to lake size, morphology, and chemistry. Although fish production data is not systematically collected, it is reported to have declined substantially over the last 60 years, even as the number of households that rely on it (estimated at 2331 in 2007) increased approximately threefold (Wetlands International 2007). The size of the *Nelumbo* harvest has declined over the last 50 years as wetland habitat has shrunk, and this was exacerbated by the September 2014 Kashmir floods that destroyed the entire population. Harvests of water chestnut and fodder, however, have increased markedly over the last 50 years, partly due to further spread of the non-native water chestnut and the increased demand for livestock feed as animal husbandry in the region has grown (Wetlands International 2007).

Recognizing the increasing environmental changes to Wular Lake and the potential of these changes to affect human communities, the state government of Jammu and Kashmir commissioned Wetlands International to prepare a Comprehensive Management Action Plan for the conservation and restoration of Wular Lake. This was published in 2007. The Action Plan recommends a range of measures including the removal of approximately 2.2 million willow trees to increase the area of the lake, dredging sediment over 27.2 km^2 to restore depth and water holding capacity, creation of a Wular Development Authority to oversee future policy, construction of sewage treatment facilities, erosion control through reforestation, creation of protected areas to support waterbirds and other wildlife, development of ecotourism, and stocking programs to bolster fisheries. The report includes an economic analysis indicating that the long-term benefits from these actions would be many times greater than the costs (Wetlands International 2007). To date, the only recommended actions taken have been the removal of approximately 30,000 willows by the end of March 2016 and dredging of an area slightly less than 1.2 km^2.

Arrival, spread, and impacts of two new invasive floating aquatic plants

A. cristata was first recorded in Wular Lake between 2002 and 2004 when it was already forming thick mats, competing with other plants, and blocking navigation (Mir and Pandit 2008; note that it was originally misidentified as *A. pinnata*, later corrected by Masoodi and Khan 2012a; Fig. 2a–c). Although *A. cristata* is not a well-known invader elsewhere, it has spread rapidly in Wular Lake and forms mats up to 10 cm thick (Table 1; Fig. 2a–c; Masoodi and Khan 2012a). Adult *A. cristata* in Wular Lake die during winter, but spores germinate in spring and mats are formed again by summer. Boat navigation has been affected by this species because it blocks channels (Mir and Pandit 2008), and the benefits from commercial fishing have declined because fishers now regularly need to hire additional labor to clear the water surface of *A. cristata* before they can cast their nets (AM, unpublished data from informal interviews with fishers; see Table 1; Fig. 2b). Some limited and poorly coordinated efforts have been made to manually and mechanically remove *A. cristata* from portions of nearby Dal Lake, but these have had little immediate and no lasting success (McDougall et al. 2011). During late 2014, the worst floods in several decades washed away all floating mats of this species, but new mats emerged in early 2015 and the species was again widespread in Wular Lake by 2016 (MA, personal observation). No quantitative survey results are available for the current extent of the species.

Alligator weed, first recorded in Wular Lake in 2008 (Fig. 2d–f; Masoodi and Khan 2012b), is a widely distributed global invader. It was introduced to India in the 1940s (Maheshwari 1965) and is now found throughout the country (Masoodi and Khan 2012b). In Wular Lake, it forms dense floating patches that likely impede penetration of light and oxygen and promote sedimentation and flooding (AWC 2010; Table 1). Patches occur most often within mats of water chestnut, and our observations (AM, unpublished data) indicate that the latter is being outcompeted (Fig. 2d, e). In 2008, there were six patches of alligator weed recorded, covering a total area of 41.3 m^2. By 2011, this had grown to 82 patches with a total area of 831 m^2 (Masoodi et al. 2013). Based on this growth, it was estimated that alligator weed would cover 90% of the lake by 2027 (Masoodi et al. 2013). The 2014 floods washed all of the floating mats of this species out of Wular Lake, but during 2015 patches of alligator weed re-emerged, particularly along the banks, and these became more widespread during 2016. The unstable political and military situation in Kashmir prevented a full survey during 2016, but the observations that could be made indicate that the species is rapidly spreading and approaching the population levels that it was at prior to the 2014 floods (MA, unpublished data). Alligator weed has also become more widespread in Wular Lake backwaters and adjoining wetlands, possibly as a result of the floods (MA, unpublished data).

Interviews with members of the local population attest to the large detrimental effects these species have had on well-being. An 80-year-old fisherman describes "life was better before the weeds were here, there was more fish and people were happier. I now lament the current state of affairs of this lake. We don't get help from the government and we cannot manage these weeds as we have to make a living and the

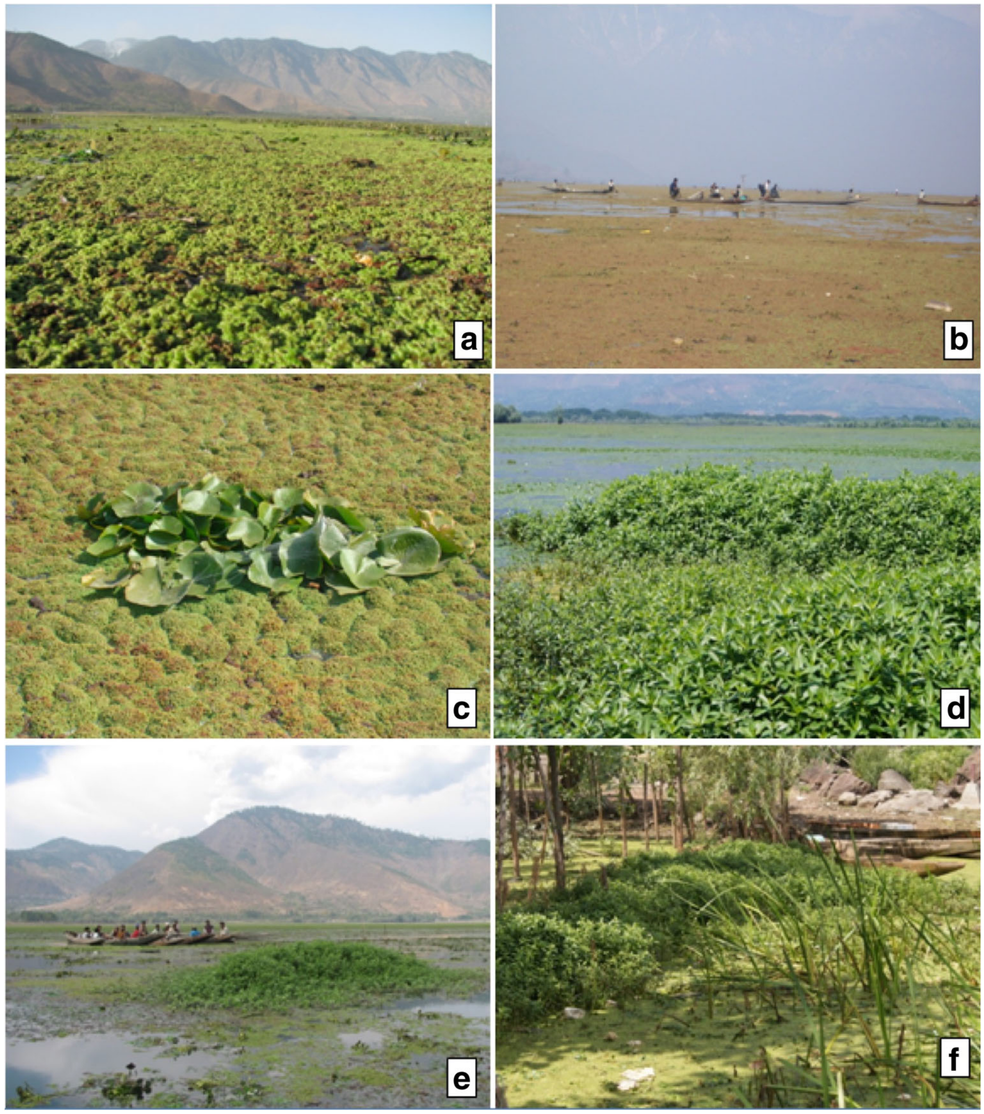

Fig. 2 Invasion of two floating aquatic plants in Wular Lake. *Azolla cristata* forms thick mats during summer (**a**) and turns red as it senesces in winter (**b**). Other aquatic plants are outcompeted by this species (**c**). Alligator weed (*Alternanthera philoxerodies*) forms large floating mats in the lake (**d**, **e**) and along the margins (**f**)

returns are too low for hard work." Another fisherman states "in the last couple of years 600-700 fisherman have migrated from these villages to Srinagar (the capital city) because weeds reduce fishing, water quality, and increase water born disease." He mentions further that the "lake has silted up and fishing is worse, and there has also been a loss of water surface area and the ability to harvest *Trapa* (water chestnuts) so some fishermen now harvest sand for a living". A local livestock owner states "the water has gone down now and our cattle feed on the weed and we suspect it is causing them to die. Water chestnut harvests have dropped as well. Both of these factors are making people poorer". Another villager adds that "because of loss of fish in the lake prices have gone up and people cannot afford it anymore." These impacts on well-being can have generational impacts, with one local fisherman stating "I was not encouraged to study by my parents because the efforts at the lake would fetch good dividends and everybody was happy. Now since these weeds have invaded, the overall resource base of the lake has declined and I am struggling to even educate my children."

Several changes to ecological components and processes, and reductions in ecosystem service provisioning, have been caused by floating aquatic plant invasions elsewhere but not yet recorded for Wular Lake (services without asterisk in Table 1). Decreases in water quality have been recorded elsewhere (see references in Table 1), and may also be occurring in Wular Lake. In particular, dense mats of floating plants reduce oxygen and light penetration into the water column (AWC 2010). This reduces populations of rooted macrophytes and aquatic animals, including fish, that rely on the oxygen and the habitat that macrophytes provide (AWC 2010). Reductions in the potential for the lake to be used for transport will become more significant if the species continue to spread, and we speculate that this will continue to hinder access for fishermen and water chestnut collectors. Invasive floating aquatic plant species have been recorded elsewhere to reduce recreation opportunities, esthetic values, and tourism (see Table 1 for references). Although Wular Lake does not currently support significant recreation or tourism, its potential as the largest freshwater lake in India and a Ramsar-listed wetland to support such activities in the future may be large (Wetlands International 2007). Thus, the invasive plants may reduce the possibilities for such industries to emerge.

Potential for control

Alligator weed is at a relatively early stage of invasion in Wular Lake, and it is possible that control efforts could reduce its range and impacts. Manual control is likely to be effective for floating mats because patches are easy to locate and entire plants can be readily removed (van Oosterhout 2007). The success of such a program would depend on how rapidly it is implemented because additional spread of the plant will increase the size of the problem and subsequent control costs. Although *A. cristata* is better established in Wular Lake than alligator weed, floating mats could be removed in the same way as alligator weed, and this may prove effective at least for seasonal control.

A program that funds manual control of the two invasive species could have several positive outcomes. First, removing the weeds would safeguard the provisioning of ecosystem services (Table 1). Second, locals could be employed to remove the weeds, leading to a direct economic gain for the population living near Wular Lake. This could be implemented in a similar manner to the *Working For Water* program in South Africa (van Wilgen and Wannenburgh 2016). One advantage that less wealthy countries have for controlling invasive species compared with more wealthy countries is a relatively low cost of labor (Nuñez and Pauchard 2010), and it is likely that many underemployed and poor fish harvesters living near Wular Lake could be readily employed to harvest the invasive species. This population already possesses the boats required to do the work. Third, rapid control would reduce the chance of this species spreading to other ecosystems. The increased supply of many ecosystem services, potential job creation, and prevention of future impacts from controlling the invasive species in Wular Lake would aid in poverty alleviation and improve human well-being. Fourth, establishment of such programs may assist in the future if additional invasive species become established.

If manual control is not successful or becomes too costly, there is potential for the use of herbicides and/or mechanical harvesters to remove the plants from high priority areas (e.g., near pipes that remove water from the lake). Herbicides could only be implemented over relatively small areas, and the costs and side effects of such work would need to be carefully considered. In the absence of manual control, the only long-term and extensive solution may be via biological control (van Wilgen et al. 2012). *Azolla filiculoides*, a congener of the *Azolla* in Wular Lake, has been effectively controlled by a North American weevil for over a decade in South Africa (Hill et al. 2008). It is possible that this agent would be effective on *A. cristata*, and there is potential for other agents to be developed. There are also established biological control agents for alligator weed (van Oosterhout 2007). We caution, however, that much research, including rigorous testing of host specificity, would be needed to determine whether biological control can be a safe and effective management option for these species in the Kashmir Valley. A particular difficulty may be that any biological control agent would need to be able to survive the cold winters.

We acknowledge that establishing, maintaining, and financing a control program for these species would present significant challenges. Although we cannot offer a full prescription for such a program, we note that there is already work underway on the Wular Action Plan (Wetlands International 2007), funded by the Government of India, and that removing invasive floating aquatic plant species would help to achieve the goals of that plan. In particular, work is underway to restore the volume of the lake through dredging and removal of willow plantations in fringing wetlands. This work will generate revenue from sale of firewood and, by increasing the water holding capacity of the lake by as much as 40%, may lead to higher revenues for hydroelectric power producers who will have greater production during winter when they currently run below capacity. For this reason, it may be reasonable for some portion of the revenue from sale of firewood and electricity be used to support a control program.

Any plan for restoration of Wular Lake and control of invasive species will need to consider potential ecosystem-service trade-offs (Rodríguez et al. 2006). We believe that manual control would have little impact on the system aside from the removal of plant species for which there are no known benefits. The use of herbicides may affect other plants and water quality in Wular Lake, and biological control organisms would need to be studied to determine whether other ecosystem services would be affected. At a larger scale, the work to remove willow plantations will substitute one ecosystem service (provision of fuelwood) for others, including an increased water holding capacity of the Lake. Dredging Wular Lake will likewise increase water holding capacity, but may affect other ecosystem services by, for example, temporarily increasing turbidity and nutrient levels. These trade-offs should ideally be fully acknowledged through community consultation before work begins. We emphasize, however, that the invasive plants discussed in this paper already have negative impacts and have no known positive impacts and that the potential for their control is declining over time. We see a need for rapid action that is unlikely to reduce provisioning of other ecosystem services.

Conclusions

Continued spread of *A. cristata* and alligator weed in Wular Lake will likely cause further decline in fish harvest. Nelumbo and water chestnut are proving to be particularly vulnerable because they are outcompeted by the new invaders. Additionally, water availability for municipal use, agriculture, and hydroelectricity generation will likely decline. These impacts will compound long-term reductions in environmental quality and ecosystem service supply, and will likely lead to increased poverty and vulnerability levels for local communities and a decrease in human well-being.

Opportunities exist to manage the invasions, and to address existing environmental issues to improve livelihoods. A program to hire locals to manually remove floating invasive plants would leverage the ready supply of labor and equipment, and if the program was well managed, the money spent would largely flow to local communities and help to diversify livelihoods. Alligator weed populations could likely be reduced over the long term. Although the prospects for manual control of *A. cristata* are less clear because populations emerge each year from seed and the longevity of the seed bank is unknown, even seasonal or local reductions would be beneficial. Beyond controlling the invasive floating plants, there is already a detailed plan for conservation and restoration in the Wetlands International (2007) report, along with an economic analysis indicating that implementing the plan would be cost-effective.

Neither the emerging environmental and socio-economic threats to Wular Lake nor the solutions suggested here are without precedent. Floating aquatic plants have proven to be some of the most damaging invasive species worldwide in terms of impacts on human welfare (Howard and Harley 1998; Aloo et al. 2013; Table 1), making it clear that large declines in human welfare may occur if *A. cristata* and alligator weed continue to spread in Wular Lake. Our suggestion to employ locals for invasive species management has precedent in the *Working for Water* program in South Africa which employs laborers to locate and cut down the invasive trees that transpire more water than native trees. This program has proven to be a cost-effective way to increase water yield, and has had large positive effects for the communities of those employed (Marais and Wannenburgh 2008; Turpie et al. 2008). While establishing and managing such a program for Wular Lake would not be trivial, the potential benefits provide clear motivation and justification for action.

The study of species invasions has increased rapidly over recent decades (MacIsaac et al. 2011), with a disproportionate amount of scientific effort occurring in North America, Western Europe, and Australia (Pyšek et al. 2008). In contrast, Asia, Africa, and South and Central America have had fewer studies and scientific publications (Pyšek et al. 2008). The latter regions are generally less wealthy, and it is reasonable to expect that the impacts of invasive species on human welfare there may be larger (Perrings 2007). Invasive species in wealthier regions of the world can devastate crops and ecosystem service provisioning, but there is knowledge and established systems, such as departments of agriculture and herbicide/pesticide manufacturers, to support farmers and harvesters as they deal with these invaders. In contrast, the economies and welfare of farmers and harvesters in poorer regions are more tightly coupled to seasonal production, and if production is affected by invasive species it can have rapid effects on food security (Perrings 2007). The population living nearby Wular Lake is highly dependent upon the fisheries and aquatic plants harvested from this ecosystem. The provisioning of these resources has been reduced by a long history of environmental degradation, with the lake itself shrinking in size and becoming eutrophic. Species invasions now threaten local human communities with losses of many important ecosystem services. Far from being an isolated example, we suspect that such impacts of invasive aquatic species on livelihoods are probably far more numerous than has been reported. We suggest that the study of invasive species impacts on human well-being should increase, as these impacts may be as damaging, and in many cases more damaging, than the ecological and economic impacts that are more often studied.

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